# CHAPTER 10
# X-RAY INTERACTION WITH MATTER

## FIVE X-RAY INTERACTION WITH MATTER

Low-Energy X-ray
- It interacts with whole atom

Moderate-Energy X-ray
- It interacts with electrons

High-Energy X-ray
- It interacts with nuclei

Five Ways of X-ray Interaction With Matter
- Coherent, Compton, Photoelectric Effect, Pair Production & Photodisintegration

Coherent Scattering
- First described by J.J. Thompson
- *Other Names:* Classical or Thompson Scattering
- *Occur At:* below 10 kEv x-rays
- The incident x-ray interacts with a target atom, causing it to become excited
- *Result:* a change in x-ray direction without a change in its energy
- Scattered X-ray $\lambda$ = Incident X-ray $\lambda$

Image Noise
- The general graying of an image
- It reduces image contrast

***Coherent scattering is of little importance to diagnostic radiology!***

Compton Effect/Scattering
- The incident x-ray interacts with the outer-shell electron & ejects it from the atom
- *Compton/Secondary Electron:* the ejected electron
- *Result:* a change in x-ray direction & reduction of its energy
- Scattered X-ray $\lambda$ > Incident X-ray $\lambda$
- *Energy:* $E_i = E_s (E_b + E_{KE})$
  - $E_i$ = incident x-ray energy
  - $E_s$ = scattered x-ray energy
  - $E_b$ = electron binding energy
  - $E_{KE}$ = electron kinetic energy

***The probability of the Compton Effect is inversely proportional to x-ray energy (1/E) & independent of atomic number!***

Backscatter Radiation
- X-rays scattered back in the direction of the incident x-ray beam
- It is responsible for the cassette-hinge image

***Compton scattering reduces image contrast!***

**FEATURES OF COMPTON SCATTERING**

| | |
|---|---|
| **Most likely to occur** | With outer-shell electron<br>With loosely bound electrons |
| **As x-ray energy increases** | Increased penetration through tissue without interaction<br>Increased Compton scattering relative to photoelectric effect<br>Reduced Compton scattering (1/E) |
| **As atomic number of absorber increases** | No effect on Compton scattering |
| **As mass density of absorber increases** | Proportional increase in Compton scattering |

Photoelectric Effect
- The incident x-ray interacts with the inner-shell electron
- *Photoelectron:* ejected electron
- *Result:* total x-ray energy is totally absorbed
- *Energy:* $E_i = E_b + E_{KE}$
- Characteristic x-rays are produced

***The photoelectric effect is total x-ray absorption!***

***The probability of the photoelectric effect is inversely proportional to the third power of the x-ray energy $(1/E)^3$!***

***The probability of the photoelectric effect is directly proportional to the third power of the atomic number ($Z^3$)!***

**Z & K-SHELL $E_b$ OF RADIOGRAPHICALLY IMPORTANT ELEMENTS**

| Element | Atomic Number (Z) | Electron Binding Energy ($E_b$) |
|---|---|---|
| Hydrogen | 1 | 0.02 |
| Carbon | 6 | 0.3 |
| Nitrogen | 7 | 0.4 |
| Oxygen | 8 | 0.5 |
| Aluminum | 13 | 1.6 |
| Calcium | 20 | 4.1 |
| Molybdenum | 42 | 19 |
| Rhodium | 45 | 23 |
| Iodine | 53 | 33 |
| Barium | 56 | 37 |
| Tungsten | 74 | 69 |
| Rhenium | 75 | 72 |
| Lead | 82 | 88 |

**EFFECTIVE Z OF MATERIALS IMPORTANT TO RADIOLOGICAL SCIENCE**

| Type of Substance | Effective Z |
|---|---|
| **HUMAN TISSUE** | |
| Fat | 6.3 |
| Soft Tissue | 7.4 |
| Lung | 7.4 |
| Bone | 13.8 |
| **CONTRAST MATERIAL** | |
| Air | 7.6 |
| Iodine | 53 |
| Barium | 56 |
| **OTHER** | |
| Concrete | 17 |
| Molybdenum | 42 |
| Tungsten | 74 |
| Lead | 82 |

**FEATURES OF PHOTOELECTRIC EFFECT**

| | |
|---|---|
| **Most likely to occur** | With inner-shell electron<br>With tightly bound electrons<br>When x-ray energy is just higher than electron binding energy ($E_b$) |
| **As x-ray energy increases** | Increased penetration through tissue without interaction<br>Less photoelectric effect relative to Compton effect<br>Reduced absolute photoelectric effect ($1/E^3$) |
| **As atomic number of absorber increases** | Increases proportionately with the cube of atomic number ($Z^3$) |
| **As mass density of absorber increases** | Proportional increase in photoelectric effect |

Pair Production

- The incident x-ray interacts with the nuclear force field
- *Results:* x-ray disappears & two electrons with opposite charge appear (positron & electron)
- *Occur At:* 1.02 MeV x-rays
- It is useful in PET

***Pair production does not occur during x-ray imaging!***

Annihilation Radiation

- A process wherein the mass of positron & electron is converted to energy

Photodisintegration

- The incident x-ray interacts directly into the nucleus
- *Results:* x-ray is absorbed by the nucleus & nucleon/nuclear fragment is emitted
- *Occur At:* 10 MeV x-rays

***Photodisintegration does not occur in diagnostic radiology!***

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## DIFFERENTIAL ABSORPTION

Differential Absorption

- Different degrees of absorption in different tissues
- *Results:* image contrast & formation of the x-ray image
- *It occurs because of:*
  - Compton scattering
  - Photoelectric effect
  - X-rays transmitted through the patient

Three Types of X-ray Important in Making a Radiograph

- Those scattered by Compton interaction
  - Doesn't provide diagnostic information
  - *Result:* image noise
- Those absorbed photoelectrically
  - Provides diagnostic information
  - *Appearance:* radiopaque
- Those transmitted by the patient without interaction
  - Provides diagnostic information
  - *Appearance:* radiolucent

Two Other Factors Important in Making a Radiograph

- X-ray emission spectrum
- Mass density of patient tissue

Image Noise

- A generalized dulling of the image by x-rays not representing diagnostic information

Radiographic Image

- It results from approximately 0.5% of the x-rays emitted by the x-ray tube

***Differential absorption increases as the kVp is reduced!***

**CHARACTERISTICS OF DIFFERENTIAL ABSORPTION**

| | |
|---|---|
| **As x-ray energy increases** | Fewer Compton interactions (1/E)<br>Many fewer photoelectric interactions ($1/E^3$)<br>More transmission through tissue |
| **As tissue atomic number increases** | No change in Compton interactions (independent)<br>Many more photoelectric interactions ($Z^3$)<br>Less x-ray transmission |
| **As tissue mass density increases** | Proportional increase in Compton interactions<br>Proportional increase in photoelectric interaction<br>Proportional reduction in x-ray transmission |

***To image small differences in soft tissue, one must use low kVp to get maximum differential absorption!***

Mass Density

- The quantity of matter per unit volume
- *Units:* $kg/m^3$ or $g/cm^3$
- *Water:* 1000 $kg/m^3$

***The interaction of x-rays with tissue is proportional to the mass density of the tissue regardless of the type of interaction!***

## CONTRAST EXAMINATION

Contrast Agent

- Compounds used as an aid for imaging internal organs with x-rays
- *Positive Contrast Agent:* higher Z than the surrounding tissue
  *e.g.* barium (Z-56) & iodine (Z=53)
- *Negative Contrast Agent:* lower Z than the surrounding tissue
  *e.g.* air

| MASS DENSITY OF MATERIALS IMPORTANT TO RADIOLOGIC SCIENCE | |
|---|---|
| **Substance** | **Mass Density ($kg/m^3$)** |
| **HUMAN TISSUE** | |
| Lung | 320 |
| Fat | 910 |
| Soft tissue, muscle | 1000 |
| Bone | 1850 |
| **CONTRAST MATERIAL** | |
| Air | 1.3 |
| Barium | 3500 |
| Iodine | 4930 |
| **OTHER** | |
| Calcium | 1550 |
| Concrete | 2350 |
| Molybdenum | 10,200 |
| Lead | 11,350 |
| Rhenium | 12,500 |
| Tungstate | 19,300 |

Low-kVp Technique
- It produces excellent high-contrast radiographs of the organs of GI tract

High-kVp Technique
- It is used to outline the organ under investigation & penetrate the CM to visualized the lumen of the organ more clearly

Double Contrast Examination
- Examination that uses air & barium for contrast
- *Examples:* pneumoencephalography & ventriculography

**EXPONENTIAL ATTENUATION**

Absorption Process
- The interaction in which x-ray disappears
- *Example:* photoelectric interaction, pair production & photodisintegration

Absorption
- The removal of x-ray from a beam via the photoelectric effect
- An all-or-none condition for x-ray interaction

Scattering Process
- The interaction in which x-ray is partially absorbed
- *Examples:* Compton effect & coherent scattering

Attenuation
- The total reduction in the number of x-rays remaining in an x-ray beam after penetration through a given thickness of tissue

***Attenuation is the product of absorption & scattering!***